NASA Capabilities That Could Impact Terrestrial Smart Grids of the Future

Electro Expo

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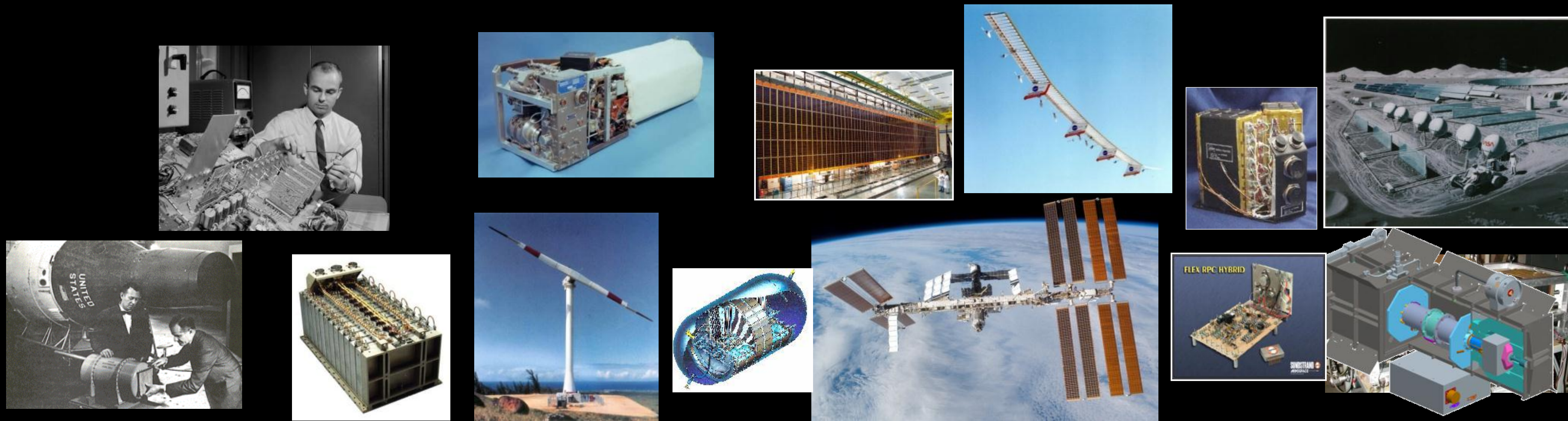
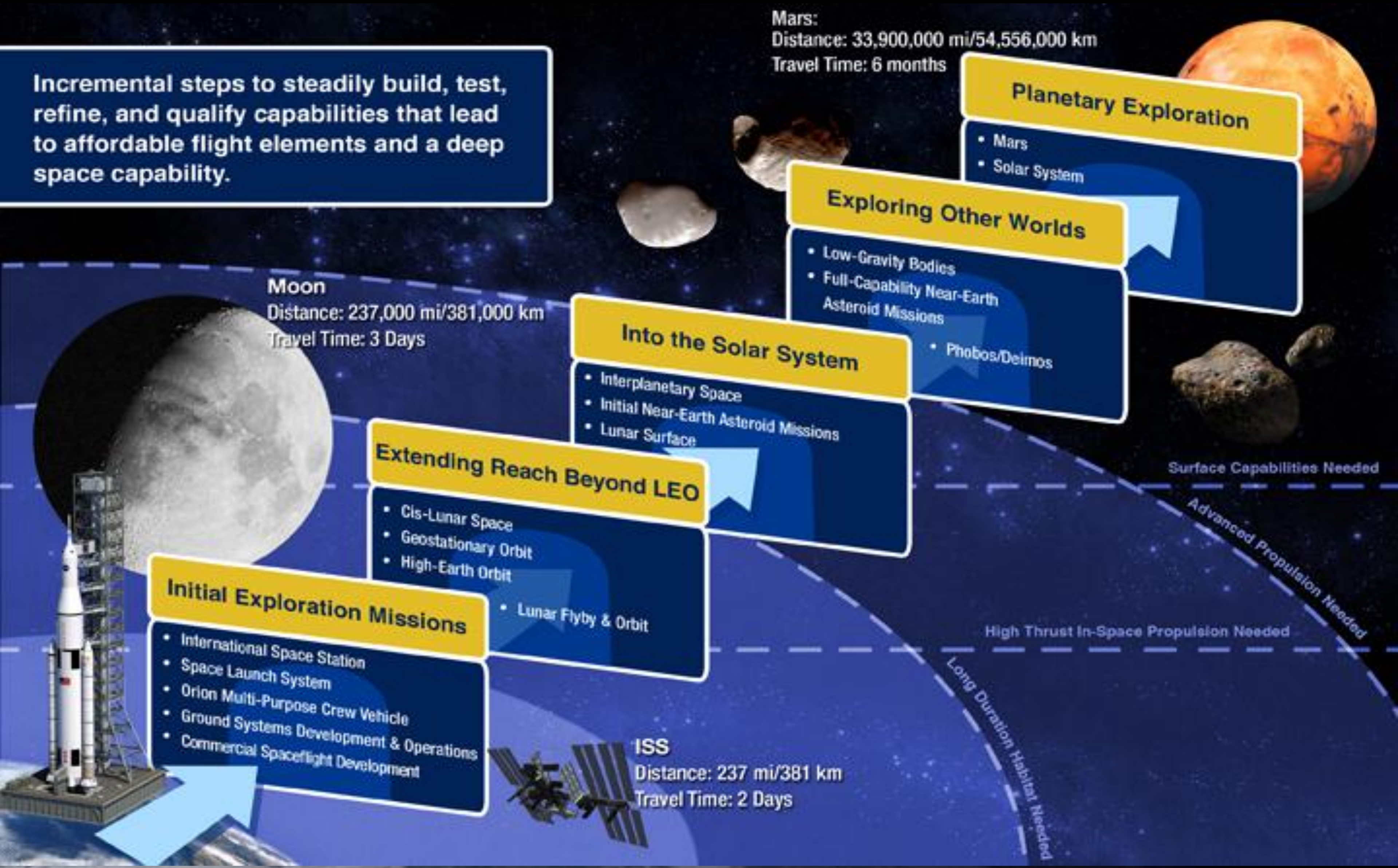
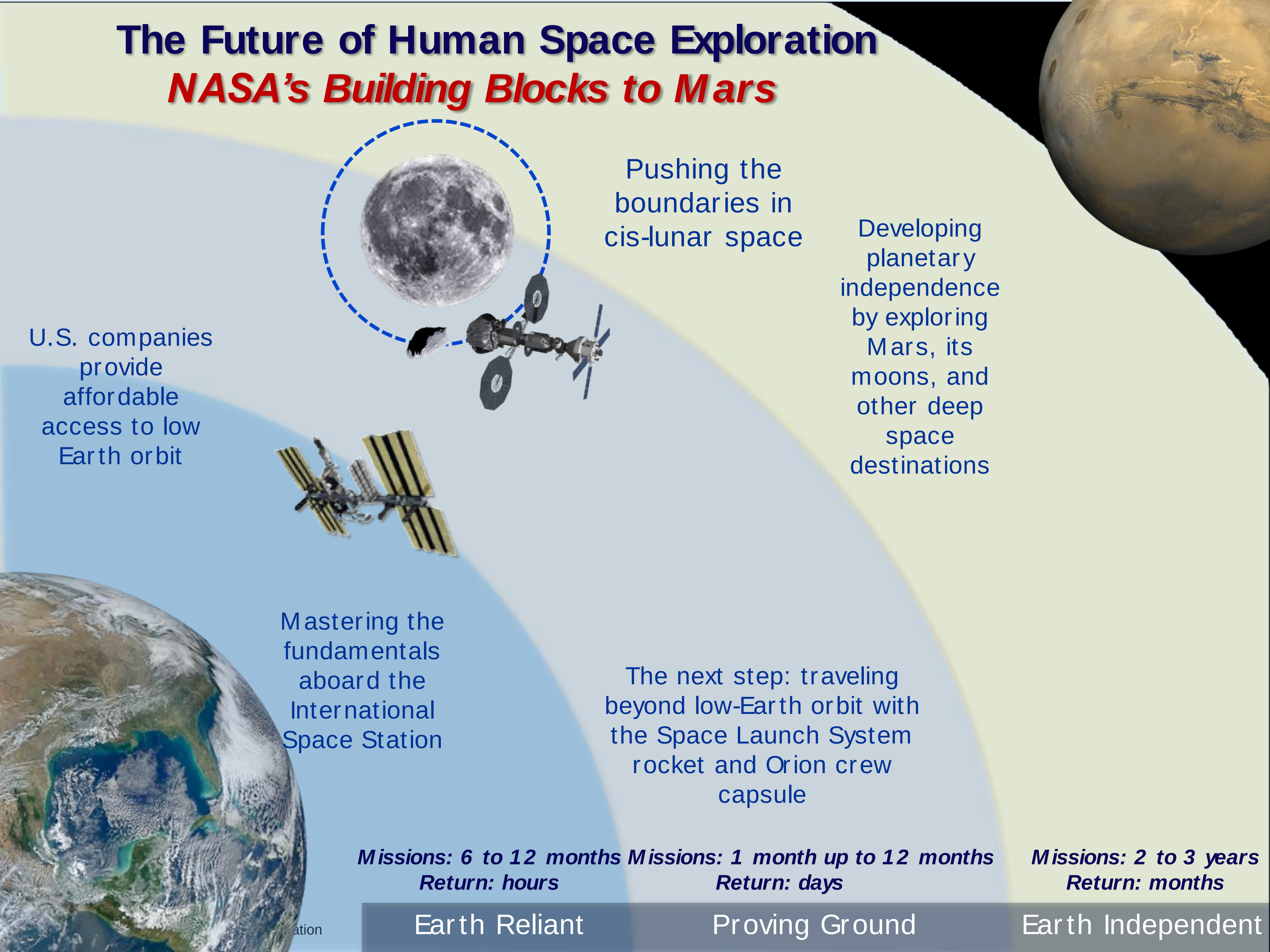
NASA Glenn Research Center
Lead Center for Aerospace Power



1960 | 1970 | 1980 | 1990 | 2000

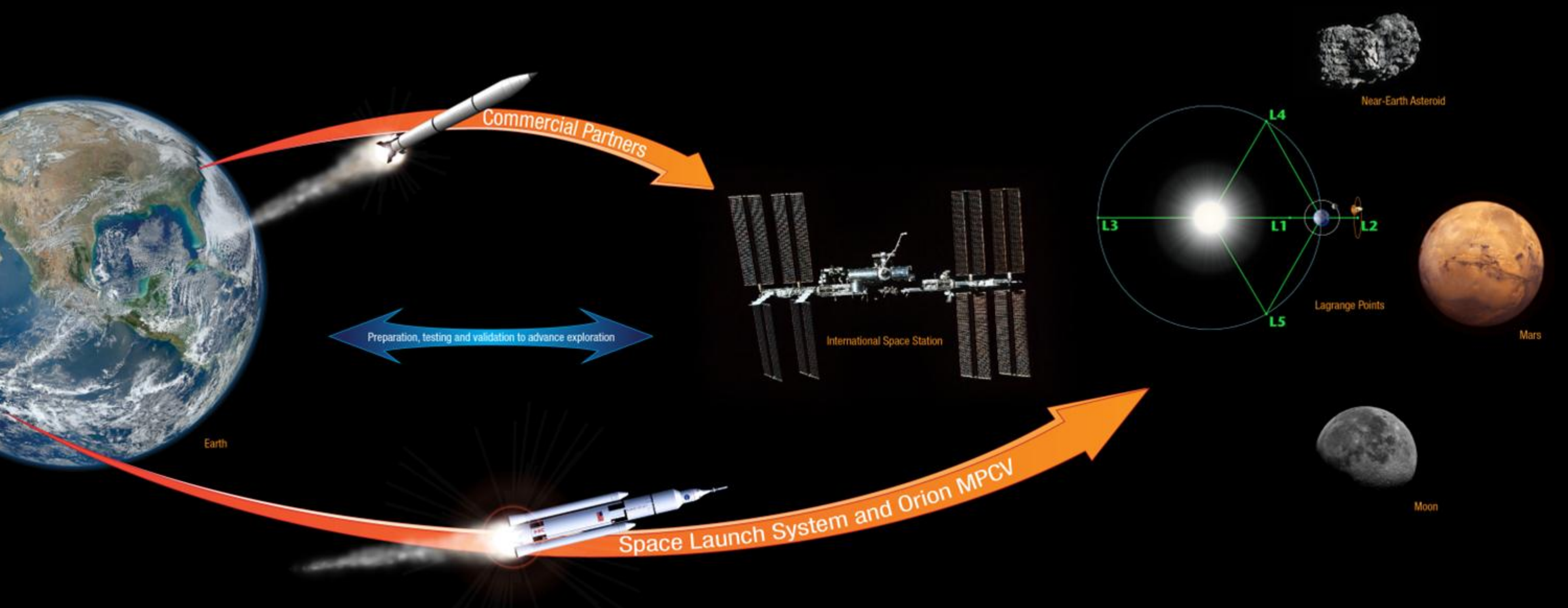
SPACE POWER


Incremental steps to steadily build, test, refine, and qualify capabilities that lead to affordable flight elements and a deep space capability.
Mars:
Distance: 33,900,000 mi/54,556,000 km
Travel Time: 6 months
Planetary Exploration
• Mars
• Solar System
Exploring Other Worlds
• Low-Gravity Bodies
• Full-Capability Near-Earth Asteroid Missions
• Phobos/Deimos
Into the Solar System
• Interplanetary Space
• Initial Near-Earth Asteroid Missions
• Lunar Surface
Moon
Distance: 237,000 mi/381,000 km
Travel Time: 3 Days
Extending Reach Beyond LEO
• Cis-Lunar Space
• Geostationary Orbit
• High-Earth Orbit
• Lunar Flyby & Orbit
Initial Exploration Missions
• International Space Station
• Space Launch System
• Orion Multi-Purpose Crew Vehicle
• Ground Systems Development & Operations
• Commercial Spaceflight Development
ISS
Distance: 237 mi/381 km
Travel Time: 2 Days
Surface Capabilities Needed
Advanced Propulsion Needed
High Thrust In-Space Propulsion Needed
Long Duration Habitat Needed


The Future of Human Space Exploration
NASA's Building Blocks to Mars
Pushing the boundaries in cis-lunar space
Developing planetary independence by exploring Mars, its moons, and other deep space destinations
U.S. companies provide affordable access to low Earth orbit
Mastering the fundamentals aboard the International Space Station
The next step: traveling beyond low-Earth orbit with the Space Launch System rocket and Orion crew capsule
Missions: 6 to 12 months
Return: hours
Missions: 1 month up to 12 months
Return: days
Missions: 2 to 3 years
Return: months
Earth Reliant
Proving Ground
Earth Independent

The Future of American Human SPACEFLIGHT

National Aeronautics and Space Administration



Human Spaceflight Capabilities

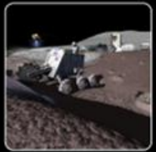
Mobile Extravehicular Activity and Robotic Platform

Deep Space Habitation

Advanced Spacesuits

Advanced Space Communication

Advanced In-Space Propulsion



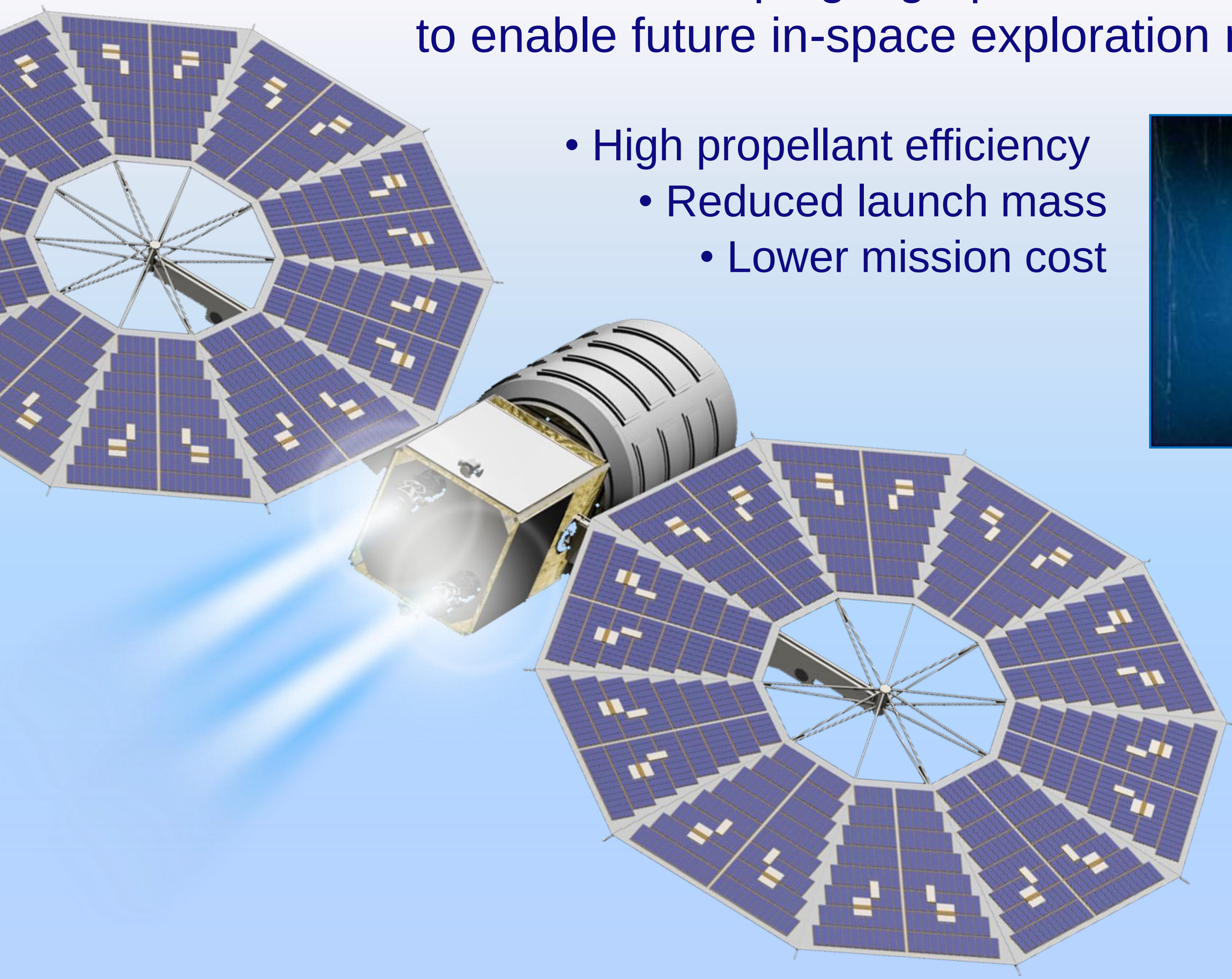
In Situ Resource Utilization

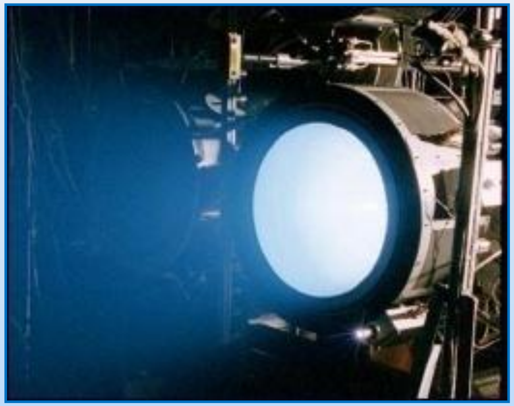
Human-Robotic Systems

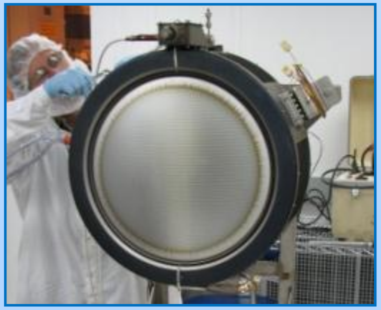
Solar Electric Propulsion (SEP)

NASA is developing high-performance SEP capability to enable future in-space exploration missions.

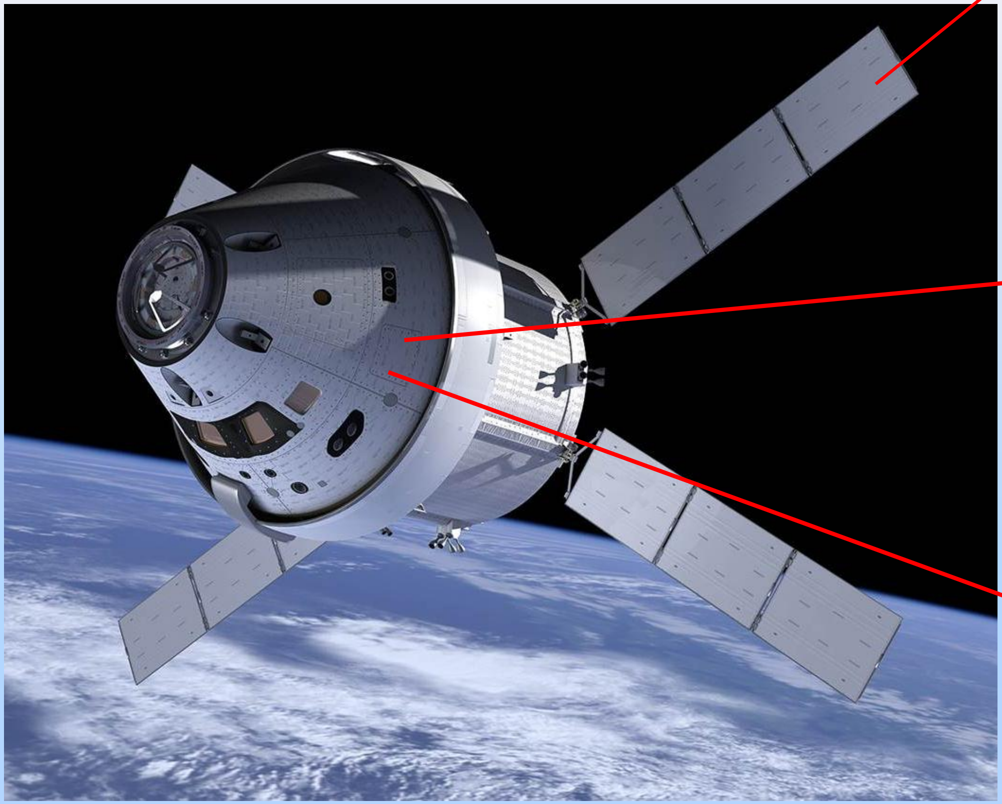
- High propellant efficiency
- Reduced launch mass
- Lower mission cost







Orion MPCV Electrical Power System



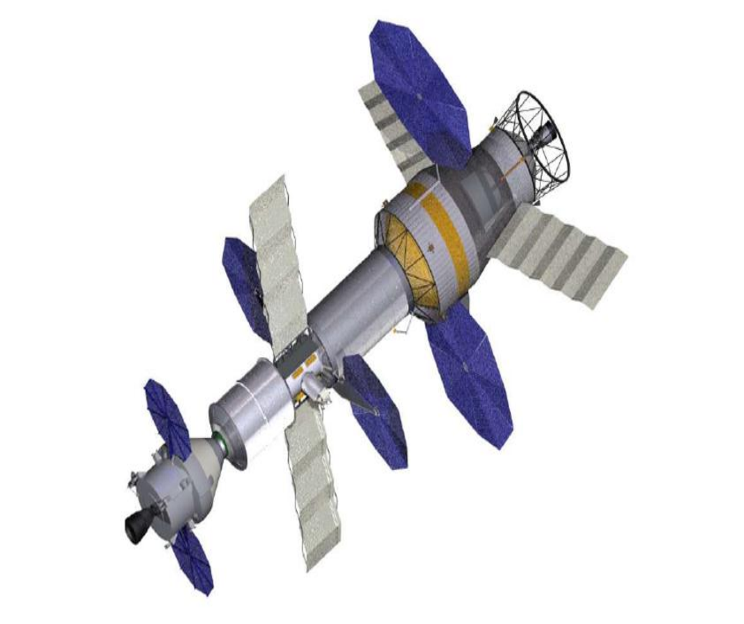
Solar Array Wings
- 4 wings with 3 deployable panels
- Triple junction solar cells for high conversion efficiency
- Two axis articulation for sun tracking
- 11.1 kW total power for user loads and battery recharge

Battery Energy Storage
- 4 batteries of ≈ 30 A-hr each
- Li ion chemistry for high energy density
- High voltage for direct connection to power distribution
- Cell balancing for high charge/discharge cycle life

Power Distribution Equipment
- 4 power distribution channels
- High voltage (120 VDC) distribution for reduced weight
- Current-limiting SiC switchgear for fault protection
- Transient protection for lightning strikes (on ground)

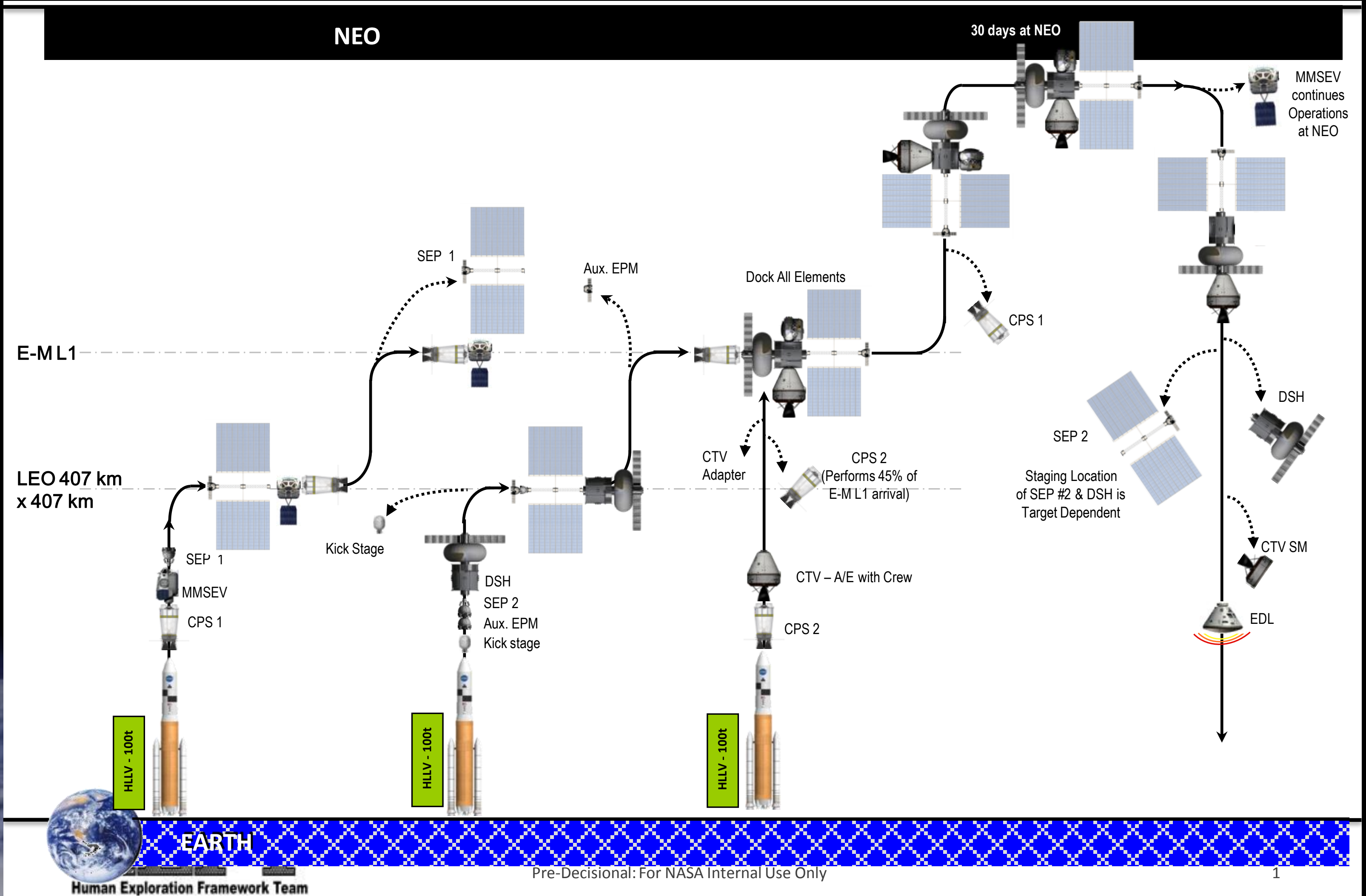
Potential Deep Space Vehicle Power System Characteristics

- Power 10 kW average
- Two independent power channels with multi-level cross-strapping
- Solar array power
  - 24+ kW Multi-junction arrays
- Lithium Ion battery storage
  - 200+ amp*hrs
  - Sized for deep space or low lunar orbit operation
- Distribution
  - 120 V secondary (SAE AS 5698)
  - 2 kW power transfer between vehicles



Deep space vehicle concept

NEO Mission Scenario

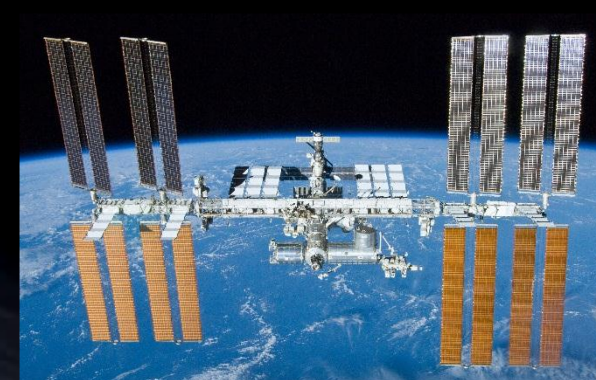


Our Challenge and Opportunity

- **Communication and recovery times are longer than any previous experience**

Mission	Duration of Mission After Incident	Communication Latency Time
Deep Space Habitat	9 months to 1 year	15 to 45 mins.
Apollo/Orion	3 – 5 days	1 to 2 sec.
Mount Everest	1 – 2 days	Real time
Deep Sea Submersible	8 hours	Real time
Shuttle	2 – 5 hours	Real time
Submarine	1 – 2 hours	Real time

- **Power Is Highest Criticality System On Board Vehicle**
  - **System will need high level of availability**
  - **System will need to operate autonomously for long periods of time**

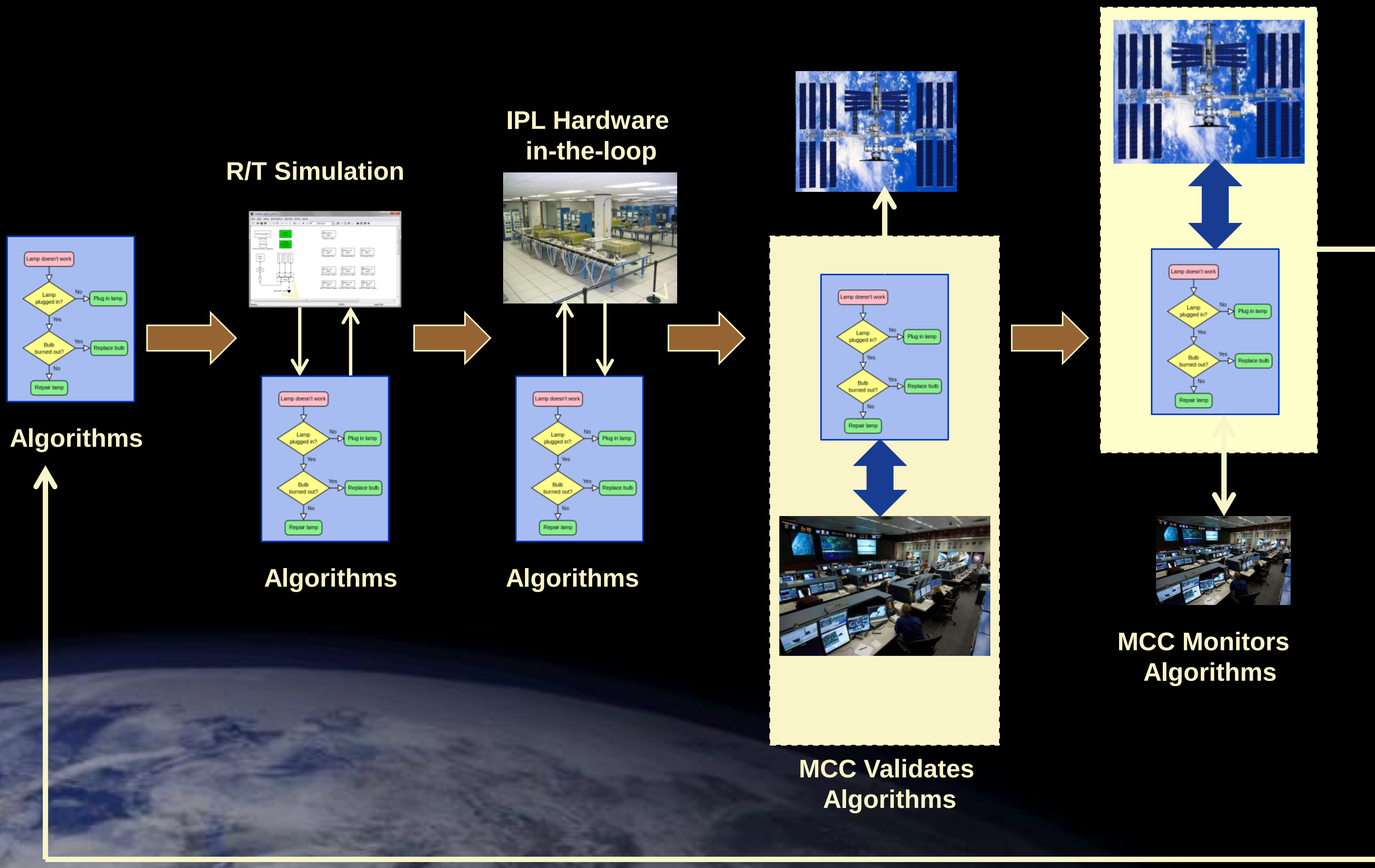


Present power systems rely on continuous real-time support from mission control

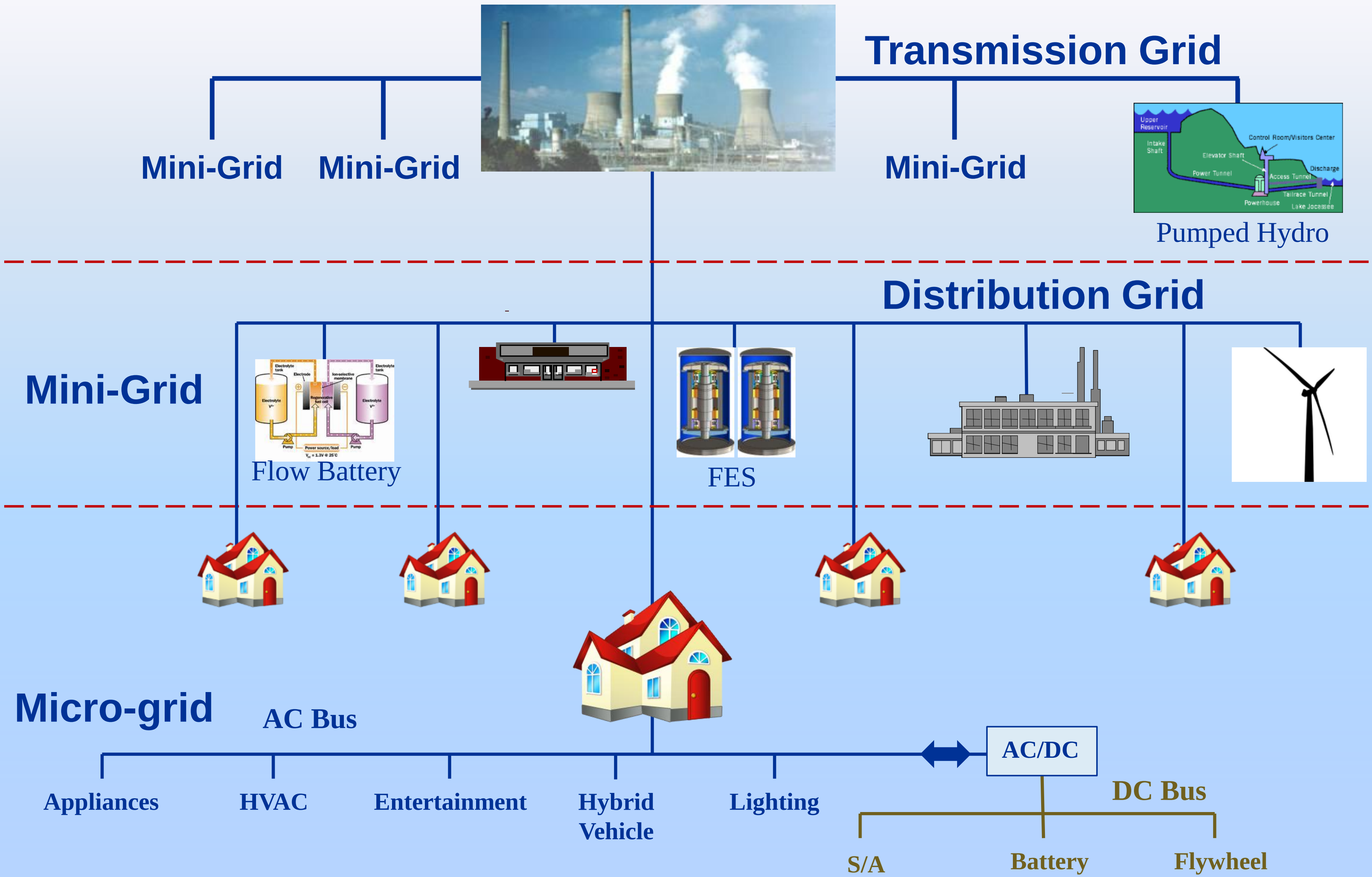
NASA Autonomy Levels

Level	Observe	Orient	Decide	Act
5	The data is monitored onboard without assistance from ground support	The calculations are performed onboard without assistance from ground support	The decision is made onboard without assistance from ground support	The task is executed onboard without assistance from ground support
4	The majority of the monitoring will be performed onboard with available assistance from ground support	The majority of the calculations will be performed onboard with available assistance from ground support	The decision will be performed onboard with available assistance from ground support	The task is executed onboard with available assistance from ground support
3	The data is monitored both onboard and on the ground.	The calculations are performed both onboard and on the ground.	The decision is made both onboard and on the ground and the final decision is negotiated between them.	The task is executed with both onboard and ground support.
2	The majority of the monitoring will be performed by ground support with available assistance onboard	The majority of the calculations will be performed by ground support with available assistance onboard	The decision will be made by ground support with available assistance onboard	The task is executed by ground support with available assistance onboard
1	The data is monitored on the ground without assistance from onboard	The calculations are performed on the ground without assistance from onboard	The decision is made on the ground without assistance from onboard	The task is executed by ground support without assistance from onboard

Algorithm Verification and Validation



Terrestrial Utility Grid Directions



AERO POWER

Aircraft Turboelectric Propulsion

Power Level for Electrical Propulsion System

Projected Timeframe for Achieving Technology Demonstration (TRL-6)

Spinoff Technologies Benefit More/All Electric Architectures:

- High-power density electric motors replacing hydraulic actuation
- Electrical component and transmission system weight reduction

>10 MW

- Turboelectric and hybrid electric distributed propulsion 300 PAX

5 to 10 MW

- Hybrid electric 737–150 PAX
- Turboelectric 737–150 PAX

2 to 5 MW class

- Hybrid electric 100 PAX regional
- Turboelectric distributed propulsion 150 PAX

1 to 2 MW class

- Hybrid electric 50 PAX regional
- Turboelectric distributed propulsion 100 PAX regional

kW class

- All-electric and hybrid-electric general aviation

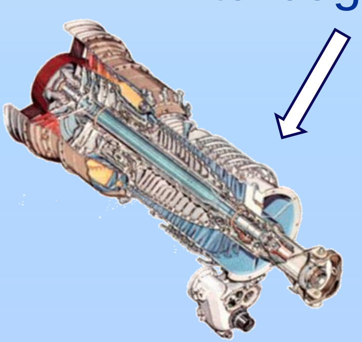
(Power level for single engine)

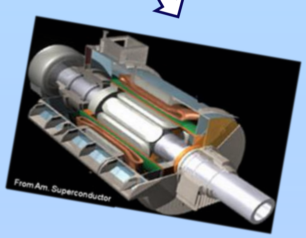
Today | 10 Year | 20 Year | 30 Year | 40 Year

Aircraft Turboelectric Propulsion

Wingtip mounted superconducting turbogenerators

Superconducting motor-driven fans in a continuous nacelle

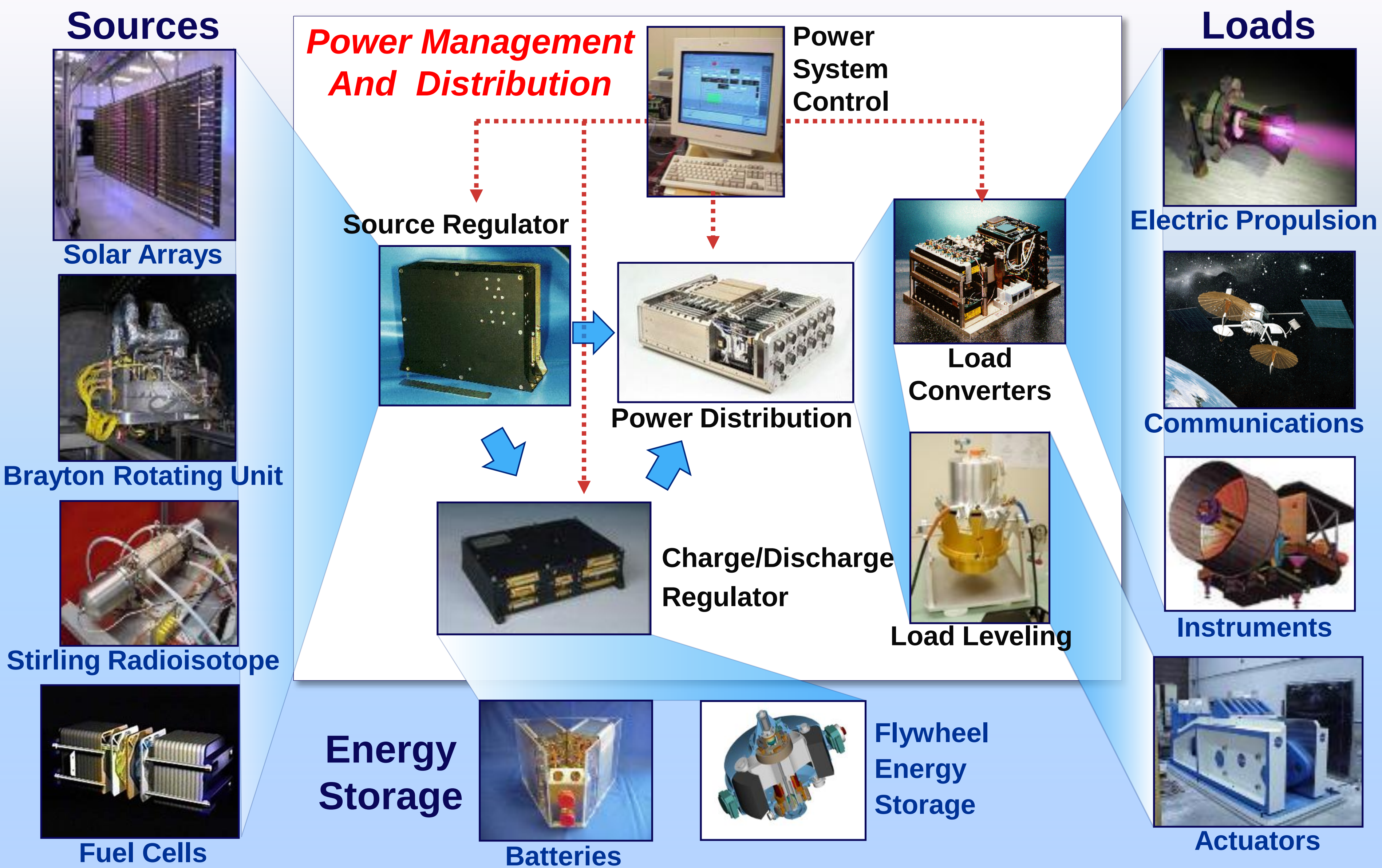




Power is distributed electrically from turbine-driven generators to motors that drive the propulsive fans.

Advanced Power Technologies Needs and Directions

Power System Taxonomy



Photovoltaic Arrays

Current State

- Solar Cell Efficiency approx. 30%
- 6 mil thick, non-flexible cells
- Relatively high cost with only limited automation

- Honey-comb panels @ 10-15 kW power levels
- Stowed volume limits power levels available

Drivers

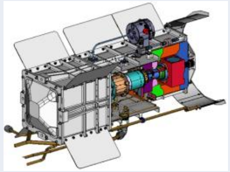
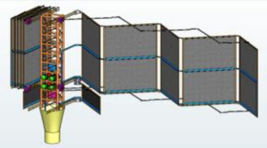
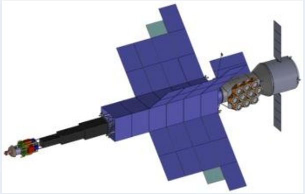
- High Power Scalability
- Higher efficiency
- Lower Cost
- Lower Mass
- Improved Radiation Resistance
- Survive Space Environments
- High bus voltage capability
- Increased Reliability
- Improved stowed volume and deployability
- High temperature/high intensity and low temperature/low intensity operation

Missions

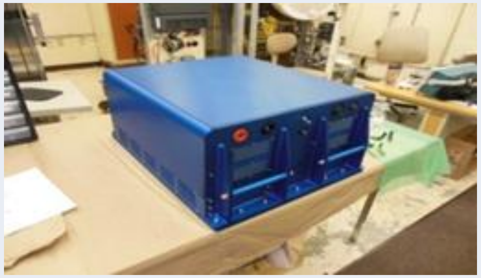
- Low cost, low mass blanket technology using automated manufacturing methods

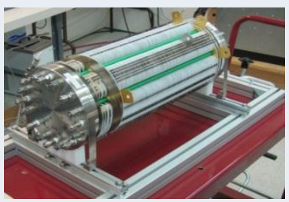
- Large multi-hundred kilowatt solar arrays w/ improved stowed volume and deployability.
- Arrays tailored for low intensity / low light operation

Nuclear Power Generation

Current State	Drivers	Future State
MMRTG • 110 W modules • Low efficiency 	• Long duration deep space missions • Greater distance from sun • Planet surface ops • Large power generations for nuclear electric propulsion • 100sW – MW needs	• Advanced Stirling Generation > 20% Conversion Efficiency  • Nuclear surface power  • Large fission for NEP 

Batteries

Current State	Drivers	Future State
• Rechargeable: Ni-H_2 (45Wh/kg, > 10 years); Li-Ion (100 Wh/kg, > 5 years life) • Primary: Ag-Zn (100 Wh/kg; 20 cycles); Li-SO_2 (200 Wh/kg; 5 years life) • Heavy, Bulky • Safety Concerns 	• Very high specific energy Rechargeable batteries to enable longer operation • Emphasis on safety • Longer cycle life • Extreme temperature environments	• "Beyond Li ion" Rechargeable Batteries: > 500 Wh/kg, 5 yrs • Rechargeable Li ion Long cycle life batteries:> 220 Wh/kg, 5 yrs • Primary: 1000 Wh/kg, > 20 yrs 

Current State	Drivers	Future State
Regenerative Fuel Cells		
• Power rating 2-10 kW • 35-50% Efficient • Life: 50 Cycles • Heavy, Bulky, Complex, Safety Concerns 	• Longer missions – days / weeks • High Efficiency • “Passive” management of fluids and gasses • High Power Rating and energy storage capability • Long Life, high reliability, safe • Operate with flexible fuels	• Power Rating: 10-30 kW >8 hrs. • Operable with reactants at > 2000 psi to reduce tank volume • Life: 10,000 hours • 70% Efficient, Reliable & Safe • Solid oxide fuel cells capable of CO_2 processing and oxygen production
Flywheels		
• Specific Energy 50Whr/kg 	• High power • Long life • High Energy Density • High Strength Fibers • Low Loss Bearings • Reliability • Mass	• Carbon fiber or Graphene specific power >200+ W-hr/kg. • Cycle life >150,000 cycles • Operating temperature • -150C to +150C

<table>
<tr><th>Current State</th><th>Drivers</th><th>Future State</th></tr>
<tr><td colspan="3">Power Conversion and Distribution Systems</td></tr>
<tr><td>• Power converters 94% efficient
• Power Distribution: 170V and 120 V
• Switchgear – Solid State, Electromechanical Relays</td><td>• Need for unique vehicle configurations
• Extreme Space environments
• Maximize efficiency, power density, safety, reliability
• Minimize mass/volume, DDT&E costs, integration and operations cost</td><td>• Modular PMAD
• Power Converter >97%
• Voltage >300V
• Novel Switching Devices
• Superconductors
• High radiation tolerance
</td></tr>
<tr><td colspan="3">Intelligent Power Management Systems</td></tr>
<tr><td>• Spacecraft power managed by ground controllers
</td><td>• Long term autonomous operations
• Load and energy management under constrained capacity
• Failure diagnostics and prognostics
• Integration with Mission Manager</td><td>
Autonomous Vehicle Management with Ground Oversight</td></tr>
</table>

Electric Machines for Commercial Aircraft Propulsion

Current State	Drivers	Future State
• Commercial aircraft use turbofans or turbo props. Electric aircraft propulsion only implemented on small experimental planes. • Motors, generators, power distribution, and energy storage to heavy and inefficient to exceed performance of baseline system	• High Specific Power Electric Machines (>8HP/lb) • High Efficiency Electric Machines • High reliability/ redundancy • High Specific Energy batteries for some configurations	• 10-100MW aircraft propulsion electric system for regional, single isle and larger commercial aircraft. • Reduced aircraft fuel burn, NOx emissions, and noise • Electric propulsion power system able to meet or exceed current safety standards (engine out, redundancy, others).